ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 46 (2014) 237 – 245

Energy Procedia

8th International Renewable Energy Storage Conference and Exhibition, IRES 2013

Multi-criteria operation strategies of power-to-heat-Systems in virtual power plants with a high penetration of renewable energies

Torsten Sowa*, Stefan Krengel, Simon Koopmann, Johannes Nowak

Institute for High Voltage Technology, RWTH Aachen University,Schinkelstraße 2, 52056 Aachen, Germany

Abstract

The integration of renewable energy into the existing energy supply system is a core challenge regarding the successful realization of the German "Energiewende". One concept to integrate decentralized regenerative power generators is a virtual power plant that operates many small facilities as one power plant. Essential parts of the concept are controllable loads and generators to reduce the impact of volatile energy resource – like wind power stations – on operational planning.

Power-to-Heat-Systems (P2H) are one possible technology that can be used to a limited extent as a controllable load. The P2H-system as a component of virtual power plants is capable of supplying flexibility due to various possible operation strategies. This flexibility can either be used for ancillary services (primary, secondary and tertiary ancillary services), to provide schedule energy or for balancing group management.

This paper presents a modeling approach for P2H systems as a component of virtual power plants with a high share of renewable energies. The operation strategies are evaluated with respect to economic and technical aspects and uncertainties in generation and load. The operation strategies of P2H systems are shown with regard to market integration of renewable energies within a virtual power plant and the provision of ancillary services.

* Corresponding author. Tel.: +49 241 80 90145 ; fax: +49 241 80 92135.
*E-mail address:*sowa@ifht.rwth-aachen.de

doi:10.1016/j.egypro.2014.01.178

Keyword: Virtual Power Plants; Operations Strategies; Power-to-Heat-Systems; Renewable Energies

Nomenclature

$x_{k,i,t}$	Power [kW] provided by Heat Storage k in Market/Product i at Time Step t

Market/Product Index i breakdown:

1	Day Ahead Market Purchases
2	Day Ahead Market Sales
3	Tertiary Reserve Positive
4	Tertiary Reserve Negative
5	Secondary Reserve Positive
6	Secondary Reserve Negative
7	Primary Reserve
8	Intraday Market Purchases
9	Intraday Market Sales

The following input parameters are needed to model the P2H-Systems:

p_k^{out}	Maximum discharging power of Heat Storage k
p_k^{in}	Maximum charging power of Heat Storage/Heating Grid k
W_k^{max}	Capacity of Heat Storage/Heating Grid k
W_k^{start}	Initial storage level of Heat Storage/Heating Grid k
U	Heat transmission coefficient (of thermal insulation) of Heat Storage$k$
T_k^{spread}	Temperature spread of Heating Grid k
T_k^{min}	Minimum temperature of Heat Storage/Heating Grid k
T_k^{max}	Maximum temperature of Heat Storage/Heating Grid k
T_k^{amb}	Ambient temperatures of Heat Storage k
HL_k^{factor}	Heat loss factor of Heating Grid k
HL_k^{empty}	Heat losses in uncharged state of Heating Grid k
D_k^{th}	Heat load of Heating Grid k
τ_{intra}	Intraday Market Grace Period

1. Introduction

In the course of the “Energiewende” the share of renewable energies in the German electricity grid is steadily increasing. In this transformation, the grid and market integration of renewable energies plays an important role. Power-to-Heat (P2H)-Systems can offer additional flexibilities to virtual power plant portfolios with distributed generation units and support the participation in day-ahead (DA) as well as in Reserve Power (RP) markets. Consequently, an evaluation of this technology as part of a Virtual Power Plant becomes necessary. For the subsequent identification and analysis of new operation strategies for P2H-Systems, a dynamic approach for a multi-market stochastic optimization model for the operation scheduling of a P2H-System in a virtual power plant is presented and evaluated in this paper.

2. Modeling of Virtual Power Plants

The modeling of P2H-Systems is an extension to an existing Virtual Power Plant (VPP) model at the Institute for High Voltage Technology. This section introduces the key features of the existing model. A more detailed description can be found in several previous publications [1-2], [4-5].

2.1. Modeling Approach

The VPP-model uses stochastic mixed integer linear programming to determine the optimal operation strategy for all decentralized units in the considered portfolio for multiple electricity markets. A bottom-up approach is used to model each unit and its distinctive technical and economic characteristics. Among the already modeled technologies are wind and photovoltaic power plants, combined heat and power units, electrical storage systems and electric vehicles.

In order to enable robust solutions under consideration of forecasting uncertainties, the model is formulated as a stochastic optimization with several stages and a rolling horizon. Schedules are revised and intraday transactions are adapted based on updated forecast information [1].

Fehler! Verweisquelle konnte nicht gefunden werden.provides an overview of the existing VPP model.

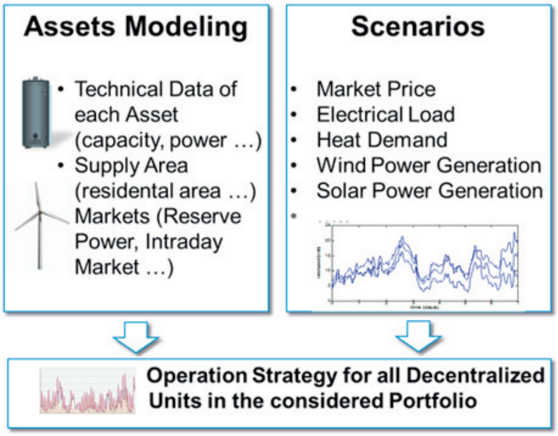

Figure 1: Model Overview

2.2 Market Operation Strategies

VPPs have access to a variety of electricity markets. They can trade energy for the following day on the day-ahead market and they can use the intraday market for short term transactions until 45 minutes before delivery. Additionally, there are markets for reserve power.

Primary, secondary and tertiary reserve can be offered on those markets, which are hosted by the German transmission system operator. All existing electricity markets are taken into consideration in the VPP model [1],[2],[5].

2.3Modeling of Uncertainties

A key feature of the existing model is an adequate consideration of forecasting uncertainties. Depending on the VPP portfolio, the following uncertain parameters can particularly influence VPP operation:

- Market price uncertainties
- Wind speed and solar irradiance uncertainties
- Load demand uncertainties

In stochastic programming, uncertainties are represented via scenarios. Scenarios for each type of uncertainty are created and finally combined to input scenarios for the VPP model. More details regarding the scenario generation method can be found in [1].

The basic principle of the stochastic programming approach is exemplarily explained based on the combined day-ahead and dispatch decision. The problem structure of the two-stage stochastic programming model is illustrated in Figure 2.

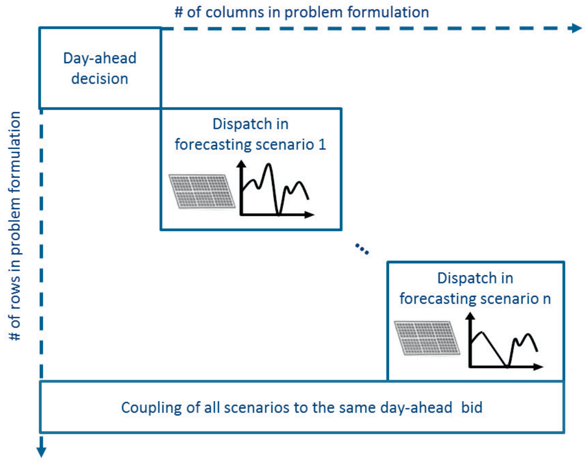

Figure 2: Problem structure of the two stage stochastic model

The first stage decision includes the day-ahead decision. The bid made for the day-ahead market has to be adhered to in all scenario realizations of the uncertain parameters like e.g. wind speed or solar irradiance. However, for each scenario a different combination of individual unit dispatch can lead to the day-ahead bid. Thus, the unit dispatch is considered in the second stage variables of the stochastic programming model. With this modeling approach the day-ahead decision will be a robust solution, because feasibility for all dispatch scenarios is ensured.

3. Modeling of Power-To-Heat-Systems

The modeled P2H-Systems consist of heat storages (HS) with individual heat generators and connected heating grids. The heating grid supplies the heat consumers, which are modeled individually. For each HS the following technical characteristics are considered within this model:

- Storage capacity
- Thermal insulation
- Maximum temperature
- Minimum temperature
- Temperature spread

Additionally, the following environmental characteristics of the technical assets and individual heat loads are taken into account:

- Ambient temperature (scenario based)
- Heat demand (scenario based)
- Existing of heat grids (demand and supply side)
- Maximum charging power

The heat which is fed into each HS is delivered by electric heat generators which alternatively are heat pumps or electric heaters. The efficiency of heat pumps is characterized through the coefficient of performance, while electric boilers are described by their overall efficiency. Heat generation is thus considered regarding the following characteristics:

- Maximum power
- Heat pumps: coefficient of performance
- Electric heaters: efficiency factor

Each heat storage is implemented with a set of decision variables $x_{k,i,t}$ describing the individual market participation.

3.1 Storage Level, Capacity and heat losses of Heat Storages

The storage capacity of each HS is defined as the amount of usable thermal energy. This amount and thus the storage capacity of the HS depend on the temperature spread of the heating grid (supply side). A higher spread also implies a higher usable thermal energy and thus the storage capacity of the HS.
The storage level of the HS is directly dependent on the average temperature of the storage medium. Due to thermal stratification, the temperature at the bottom and at the top of the storage tank remains approximately constant (T_k^{max} andT_k^{min}). At the top of the tank the storage medium is fed out at the constant temperature ofT_k^{max}. Thus, the empty storage state is reached when the average temperature in the HS drops toT_k^{min}. Equivalently, the HS is fully loaded when an average temperature of T_k^{max} is reached. Since the storage capacity and the temperature spreads are input parameters, these values have direct impact on the dimensions of each HS, which is in turn an important basis for the calculation of heat losses $\dot{Q}_{v,t}$. This calculation refers to the heat transmission coefficient U of the insulation, the temperature spread between the environment ($\theta_{HS,t} - \theta_{a,t}$) and the surface of the storage tank:

$$\dot{Q}_{v,t} = U \cdot A \cdot (\theta_{HS,t} - \theta_{a,t}) \quad (1)$$

3.2 Heating Grid (demand side) and Heat Load

The demand side heating grid obtains its thermal energy from the supply side heating grids of the heat storage. It supplies every connected heat consumer with district heating. Additionally, all heating grids in this system have a certain heat capacity which grants additional freedom in operation planning. Uncertainties in heat demand are stochastically modeled under consideration of different scenarios of heat demand.

3.3 Maximum Power Constraint of Heat Generators

An important limiting factor is the maximum input power $P_k^{in,max}$ of the heat generators. Every generator obeys constraints to consider these limitations for every time step (given a simulation time of n time steps):

$$\left(\sum_{i\in\{1,3,5,6\}} x_{k,i,t}\right) - x_{k,9,t} \leq P_k^{in,max} \;\; \forall\, t = [1,n] \quad (2)$$

These constraints are important when the maximum demand of input power is requested. This case is characterized by day ahead market purchases, full negative reserve power calls with corresponding intraday market sales and no positive reserve power calls.

4. Market Strategies

There are several market operation strategies to ensure a certain state of charge of HS on the one hand and to enable P2H-Systems to offer positive reserve power and to execute intraday market sales on the other hand.

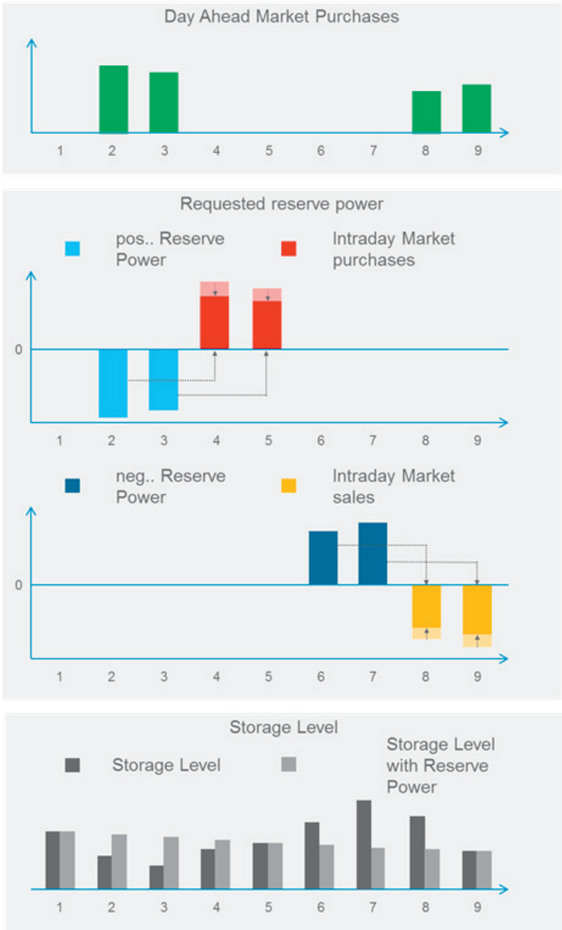

Figure 3: Market Operation Strategies

Positive reserve power can only be provided and intraday market sales can only be performed via simultaneous Day Ahead Market purchases and a corresponding reduction of power consumption of the electric heat generators when reserve power is actually dispatched. Afterwards, recently called-off reserve power is compensated, under consideration of additional heat losses, through intraday market transactions. In case of positive reserve power, dispatched power is compensated through intraday market sales. Accordingly, in case of negative reserve power, compensations are conducted through intraday market adjustment. For more information about these strategies see [2],[5].

5. Results

As an exemplary analysis of a VPP with a high share of renewable energies, a group of wind energy plants and a P2H-System are considered. Stochastic influences from feed-in forecasts and heat loads are considered within the VPP schedule optimization. The parameters of the considered P2H-System based on [6] are listed in Table 1.

Table 1. Parameters of P2H-System

	Power	Capacity	ΔT
P2H-System	25 MW	50 MWh	50 K

The heat load is based on probabilistic load profiles as used in [3] for a week in January.

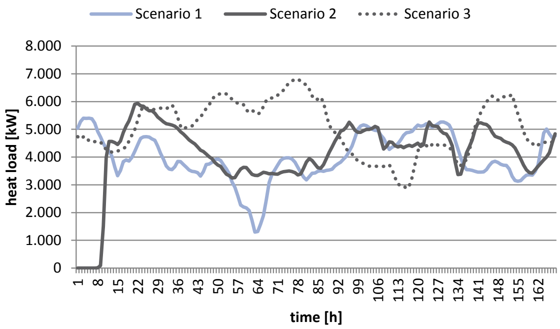

Figure 4: Heat Load Scenarios:

Based on [7], wind power systems are considered with an electric power of 1,65 MW. In this context, scenario based wind speeds [1] are taken into account (Figure 5).

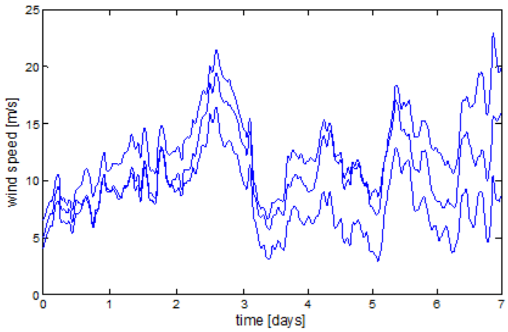

Figure 5: Wind Power Scenarios

The multi-market operation strategy of the VPP aims mainly at providing negative secondary reserve power. Primary reserve is neglected by the optimization because of its high requirements regarding the 168 h time slice in theGerman market.

Intraday market operation leads to an effective storage usage of the P2H-System, because the uncertainty regarding the storage level caused by providing reserve power is limited through Intraday market transactions (Figure 6).

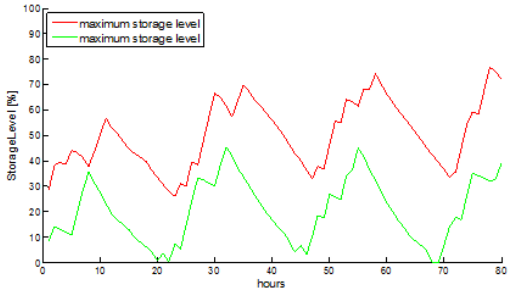

Figure 6: Storage Level of HS

The influence of the wind power and heat demand scenarios on the operation scheduling is evaluated using standard stochastic programming quality metrics. These metrics are the value of the stochastic solution (VSS) and the expected value of perfect information (EVPI). The EVPI represents the amount one would be willing to spend for the acquisition of a perfect forecast for wind supply and heat load. The VSS quantifies how much it is worth to know the distribution of the stochastic parameters. Table 2 lists the results of the different simulation runs. Each run (perfect information, stochastic and deterministic) is described by its objective Value (ObjVal), its calculation time (CPU time), its iteration needed for finding the optimal solution and the number of equations and variables.

Table 2.Summary of Results

	Perfect Information	Stochastic	Deterministic
ObjVal [€]	168.693,31	118.822,05	37.950,57
CPU Time [s]	33,85	111,00	37,85
Equations	33.036	297.324	33.036
Real Variables	75.072	1.754.460	75.072

The results show a significant difference between the deterministic and the stochastic solution. Due to the loss of information in the deterministic modeling approach the operation scheduling of the virtual power plant does not have to be feasible, resulting in an inferior performance due to the implementation of penalty terms.

6. Discussion and Conclusions

The paper describes a stochastic model for the analysis of multi-market operations scheduling for different technologies in a virtual power plant. This contribution focuses on the modeling of P2H-Sytems as part of a virtual power plant. The bottom-up modeling approach ensures a valid schedule for each unit in the portfolio taking into account technical constraints. Uncertainties in the heat demand forecast are considered via scenarios in the stochastic optimization model. The stochastic programming approach creates a robust solution.

The quality metrics of stochastic programming metrics, expected value of perfect information and value of the stochastic solution, has quantified the effects of heat demand and generation forecasts. Overall, the results are consistent with the tendency in literature for stochastic optimization und operation scheduling of virtual power plants [8].

Future work will include the modeling of further technologies, integration of risk management methods and developing a case study for a virtual power plant with grid constraints.

References

[1] Pollok T, Sowa T, Koopmann S, Raths S, Schnettler A: Evaluation of business cases for renewable generation under consideration of virtual power plants, 6th International Renewable Energy Storage Conference and Exhibition, 2012

[2] Raths S, Pollok T, Sowa T, Schnettler A, Brandt J, Eckstein J.: Market Potential Analysis of the Provision of Balancing Reserve with a Fleet of Electric Vehicles, 22nd International Conference on Electricity Distribution, 2013

[3] Krengel S, Meinerzhagen A, Falke T, Dietrich C, Witte A.: Planungsverfahren zur effizienten Energieversorgung in Mittelstädten, Internationaler ETG-Kongress, 2013

[4] Pollok T, Krüger E, Koopmann S, Schnettler A: Grid and market related integration of renewable generation under consideration of virtual power plants, 22nd International Conference on Electricity Distribution, 2013, pp. 1-4.

[5] Koopmann S, Wasowicz B, Raths S, Pollok T, Schnettler A, 2012: "Evaluating multifunctional storage usage for the integration of renewable energies", 7th International Renewable Energy Storage Conference, Proceedings, pp. 1-5.

[6] Bilfinger Bohr- und Rohrtechnik GmbH: „Wärmespeicher“, URL: http://www.bur.at/ referenzen/waermespeicher/ [03.09.2013]

[7] Wizelius T: „Developing Wind Power Projects. Theory and Practice”, London: Earthscan, 2007.

[8] Maggioni F, Allevi E, Bertocchi : (2012) :Measures of Information in Multi-Stage Stochastic Programming, Stochastic Programming E-Print Series, 2012